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SUMMARY

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A Remote Interaction system, to augment manned space travel, is proposed. It would comprise efficient remote extensions of man's important sensory and motor functions. For example, a television "remote-eye" system meeting the sensory requirements of the eye to the same extent that high-fidelity binaural sound systems can meet the sensory requirements of the ear. It may be possible to make these systems by carefully analyzing the sensory and motor mechanisms of the body, and designing each extension to be as closely matched as possible to the corresponding human system. Remote extensions of man's principal senses and motor functions would allow him to interact with an environment remote from his body -- for example the moon or planets -- almost as well as if he were physically present at the remote location. The range of a fully effective system would probably be limited by transmission delays to about 10,000 miles. This would be sufficient to allow Remote Interaction from earth to earth orbit, or from a spacecraft in lunar orbit to the lunar surface, or from planetary orbit to a planet surface. The advantages of an effective Remote Interaction system, in relation to our program of space exploration and exploitation, might justify the substantial effort that would be required to develop this system.

INTRODUCTION

A significant portion of our space program is devoted to manned operations. A more or less defined set of goals for space exploration and exploitation has been formulated, and manned operations are a part of the program that will lead to the attainment of these goals.

It must be recognized that there are two distinct classes of space goals. The first involves political and emotional considerations associated with the intensely human aspects of manned flight. A crude example -- 'getting to the moon ahead of the Russians'. The second is the execution of fairly specific tasks such as the operation of an orbital space station, and the exploration of the moon and planets. Failure to separate out these two quite different kinds of objectives can lead to confusion, and possibly to the adoption of programs that are not the optimum method of attaining the space goals we have set before ourselves.

This article is devoted solely to consideration of the means available for the realization of the second class of space goals -- essentially the exploration and practical exploitation of new environments. The elimination of the first set of goals is not, in any way, to be regarded as implied criticism. These goals are important -- similar considerations have been associated with most of man's great enterprises throughout history -- but they are outside the context of the arguments to be developed here.

REMOTE INTERACTION

Man's normal interaction with his environment may be regarded as a closed loop information exchange process, as illustrated in Figure 1. Man absorbs information from the environment via his senses, processes it, and then -- according to his preconceived goals or will -- exerts an effect on the environment by means of his motor capabilities. This effect may be by hand, foot, speech, facial expression, etc. Essentially the 'effect' is a return to the environment of information from the man.

The to-and-fro information flux can be recognized within the body itself where the loop is closed by the brain -- which is functionally connected to the outside world solely by data links.

The analogy between man's interaction with his environment and a typical feedback control system (as illustrated in Figure 2) has been recognized for some time. The three basic elements of each system are:

- (1) information sensing devices.
- (2) motor devices.
- (3) central data processing system.

In the layout design of inanimate feedback control systems, the central data processing device is located wherever is most convenient. If there are special difficulties associated with its location close to the environment which is being controlled, it may be located remotely, and connected to the sensing and motor devices by information transmission lines.

Analogously, man may wish to interact with a remote environment when there are special difficulties associated with his actual physical location at the environment. He may do so by mail, or by telephone, (both potentially information exchange processes) or even by a combination of television and remote manipulators.

Two very important limitations of most remote control arrangements are noted: (1) The remote sensory and motor devices are very inefficient, or are coupled very inefficiently to man's sensory and motor organs. For example, television is very inadequate as a remote extension of the visual sense. Less than 1/2% of the total retinal surface is activated by the image of a 500 line television picture, under normal viewing conditions. (2) In most remote control situations an extra control loop is involved. The man is in contact with both his local environment, and the remote environment.

The result of the first limitation is that the effective data rate between the man and the remote environment is inevitably less than in the case of the normal interaction of a man with his environment. With television, for example, only a very small fraction of the data capacity of the visual sensory channel to the brain is used to convey information from the remote environment.

The second limitation means that the brain does not operate in its normal mode in relation to the remote environment. When the central data processing unit in an inanimate feedback control system is located remotely, the form of the loop is not changed. The control unit receives data only from the remote sensor and can actuate only the remote motor device. Thus, for such inanimate control systems, remote operation can be made virtually indistinguishable from non-remote-operation. In the conventional human remote control arrangement, on the other hand, the brain receives data both from the remote and local environments, and generates motor activity directly only in the local environment. Thus quite apart from any limitation that may exist in the data links, the brain cannot operate in relation to the remote environment, as it would were the man actually located in that environment.

In ordinary remote control systems, therefore, man does not have a true "remote presence" capability because he is mainly in contact with his local environment.

It is the purpose of this article to draw attention to the theoretical and practical significance of the concept of Remote Interaction -- a system that may allow a man to function in a remote environment without actually being there.

THEORETICAL SIGNIFICANCE OF REMOTE INTERACTION

An ideal Remote Interaction system is defined as a system in which zero delay, distortionless information links (including sensors and transducers) are provided for all of the human sensory and motor contacts between a man and a remote environment. The arrangement of the sensors and transducers at the remote location would be in replica of the human form.

A man using such a system would, by definition, suffer a subjective experience of the remote environment identical to that of normal on-the-spot contact with the environment. Furthermore, his ability to perform any task in the remote environment would be judged, objectively, as being identical to his normal on-the-spot functional capability. It may be

noted that in Remote Interaction, both the limitations of conventional remote operations, discussed earlier, are absent.

The purpose of going to the moon or planets is not to locate the human body at these places but to place a human into normal contact with these environments. At present this can only be done by travel. Thus space travel has become synonymous with our space goals. Remote Interaction, by virtue of its definition, is a completely equivalent alternative to travel and for this reason is, at least, of theoretical significance. Travel means relocation of the body, and thus of the sensory and motor organs. Provided that distortionless extensions of the senses and motor organs are available, the total effect of body relocation can be obtained without transportation of the human body.

PRACTICAL SIGNIFICANCE OF REMOTE INTERACTION

An ideal Remote Interaction system is clearly impractical. It might also be thought that the best possible practical approach to it would be a very expensive system, very difficult to make, that would be so inferior to the theoretical ideal as to be of little value.

This may not be so however. In the first place, very little serious engineering effort has been devoted to the technological problems of providing efficient remote extensions of the human senses and motor organs. High fidelity sound probably represents the only well developed sense (hearing) and motor (speech) remote extension system. It is suggested that there are no insuperable problems involved in making efficient extensions of most of the other important senses and motor organs. The data rates of the senses appear to be within the state-of-the-art. Likewise the important motor systems of the body involve only a relatively small number of pivot points and degrees of freedom. Although construction of an adequate Remote Interaction system might well prove to be a major undertaking, there does not appear to be any fundamental physical limitation involved that could make it impossible. The approach to be followed, in developing the various sensory and motor extensions, would certainly involve an engineering analysis of the corresponding human systems, in order that high coupling efficiency be attained. As will be described later, probably the

most difficult sensory extension system to construct -- remote vision -- becomes, at least potentially feasible when the system structure of the human visual mechanism is understood.

Secondly, the magnitude of the development program needed to construct a Remote Interaction system must be judged in relation to the size of the total space program. Any method of space exploration seemed infeasible to many people only a few years ago. The conventional method now being pursued, of transporting a man to the remote location and bringing him back again, itself requires a prodigious technological effort. Should it be possible, therefore, to use Remote Interaction to augment manned operations, development of a Remote Interaction system might well prove to be economic.

Thirdly, the limitations of a practical Remote Interaction system -- which must necessarily be inferior to the idealized conceptual system -- should be judged against the very real limitations of direct, manned exploration. It must be recognized that man will never be able to explore the moon or planets in the same sense that our ancestors explored the jungles of Africa or the polar regions. He will always have to wear a space suit of some form and the full range of his sensory and motor capabilities can, therefore, never be brought into natural contact with all these extraterrestrial environments. Remote Interaction could actually prove to be a more 'natural' way of exploring certain alien environments, since the sensory and motor organs may thereby be brought into contact with the environment more effectively than would be possible directly through a cumbersome life-supporting space suit. There are some environments in which man may never be able to locate his body no matter how well protected he may be.

The practical significance of the concept of Remote Interaction is, therefore, that construction of a practical Remote Interaction system -- although a major undertaking -- appears to be technically feasible; the very special difficulties and inherent limitations of manned exploration of extraterrestrial environments suggest also that it might be worthwhile.

As a first step, towards practical implementation of the concept, the overall requirements of the sensory and motor links and transducers may be determined for a Remote Interaction system adequate either

- (1) to perform a very narrow range of tasks, e.g. to use a wrench,
- or (2) to perform a range of tasks, e.g. to assemble a space station,
- or (3) to provide a wide range of human skills and sensory capabilities as might be required to explore and exploit an unknown environment such as the Martian surface.

From the specifications of the necessary transmission links and transducers, an estimate can be made of the practical feasibility of this approach. The advantages and disadvantages of Remote Interaction in terms of functional performance and cost, can be balanced against the corresponding advantages and disadvantages of the conventional method of physically transporting an astronaut into the remote environment.

ILLUSTRATIVE SYSTEM

The physical implementation of the Remote Interaction concept could be a remotely controlled Robot, fitted with sensory detectors corresponding to all the principal senses -- e.g. vision, hearing, finger touch, etc., but excluding the myriad touch and pain sensors all over the body that, while essential for the maintenance of the body, are not really involved to any significant extent in man's interaction with his environment. The Robot sensory detectors would be coupled to the senses of the man controlling it. Thus the man would have a "Robot's-eye-view" of the Robot's environment. He would see nothing of his own local environment -- a remote visual capability far better than ordinary TV is postulated. The muscular action of the man, by hand, arm, finger, etc. would be monitored and made to command identical Robot limb motion. As the man moved his arm and fingers, he would feel his own arm move (kinesthetic sense) but it would be the Robot limbs that he would see moving and they would appear to fall within his field of view just where he would expect to see his own limbs were his eyes free to monitor the local environment. If the Robot's hand should come into contact with an

object in the Robot's environment, the man would experience a sensation of touch which would correlate well both with his visual sense showing the Robot's hand touching the object, and also his kinesthetic sense of hand position. In this way a large fraction of the significant sensory cues would be duplicated. The number, form, and kind of data inputs would be engineered into the human system; the human data processing and control mechanism (i.e. the brain) would be operating in its normal mode. The man would -- to a large extent -- be in effective contact with the remote environment through the body of the remotely located Robot: he would feel himself to be "in" the remote environment.

The various subsystems of this Robot system are considered below:

Senses

Vision

Vision will generally be the most important sense -- in the present context -- because it represents the largest single sensory channel capacity into the brain.

The inadequacy of ordinary television as a remote extension of the visual sense is evident both physiologically and by practical experience. Only 1/3% of the retinal surface is covered by a 500 line television picture under normal viewing conditions. Thus most of the 10^6 optic nerve fibers that link the retina to the brain are not used. The extreme impairment of general visual capability imposed by the narrow field of an ordinary TV system can be readily appreciated by artificially constricting the field of the eye from the normal value of about 180° to the same size as a TV screen at normal viewing distance -- i.e. about 9° . It will be found that functional performance in carrying out many everyday tasks is then very adversely affected.

In spite of the apparent inadequacy of television, the actual data flux is high. Thus in domestic television, approximately 7×10^6 resolvable picture elements are displayed per second.

The actual data rate to the brain from the retina must also be of this order, since there are only about 10^6 optic nerve fibers and the reaction time of the eye is between 1/10 and 1/100 second. Thus it appears that the inadequacy of television is not due to a limited data flux capacity, but rather to the fact that the television picture is not matched to the retina. It is of uniform quality (in resolvable elements per unit area) whereas the perceptive capability of the retina is very non-uniform. The use of ordinary television as a remote viewing device in a Robot system appears to represent an extremely poor man/machine interface design.

A television system for the Robot should be constructed in which the television image itself is stabilized on the retina, independent of eye motion, with the optical axis of the camera slaved to the angular attitude of the viewer's eye. In this way the image of the remote scene would not be stabilized, but would move over the retinal surface in just the same way as if the eye were observing the remote scene directly. With the television image stabilized on the retina however, the video data flux could be tailored to the sensory requirements of each part of the retina -- thus allowing a much greater area of the retina to be covered without unduly increasing the total data flux through the television system.

A television system of this type would require measurement of the direction of pointing of the eye of the viewer, with use of this information to control both the projection of the monitor image into the eye and the angular attitude of the camera axis. Experimental techniques are already available for measuring eye motion and could be developed into a suitable operational form.

The optical axis of the remote television camera would move like a remote eyeball, constantly flicking over the viewed scene in response to the motion of the viewer's eye. Transmission delays between the man and the Robot would probably limit the range of

this system to about 10,000 miles. At this range there would be a delay of about 1/10 second between a movement of the eye and a corresponding movement in the received picture.

It is recognized that not enough is known of the nature of peripheral vision to enable the most efficient match possible to be made between the retina and the television system. However, enough is known to enable a considerable improvement to be made over present television systems. Research, to find more exact qualitative and quantitative descriptions of peripheral vision, would undoubtedly be an important part of a program to fully develop this form of remote viewing.

Touch

From the point of view of providing remote manual dexterity, sense of finger touch would be an important part of the Robot system.

The remote Robot would be fitted with a number of touch sensors on its fingers, and these would be linked to corresponding touch stimulators fitted to the fingers of the man controlling the Robot. It is estimated that a fairly small number of touch sensors, less than 100, would provide an adequate remote sense of touch for both hands.

Balance

To some extent this could be a "subconscious" closed loop within the Robot itself. This would tend to mitigate stability problems arising from the 1/10 second round trip communications delay at the 10,000 mile maximum range. The remote visual sense would contribute balance cues. Inertial sensors could be included to monitor angular rates as necessary.

Hearing

This might be useful for certain applications and would obviously be a very easy sense to instrument.

Motor Functions

Arm, Hand and Finger Motion

The man controlling the Robot would be fitted with sensing devices to monitor the position of his arms, hand and fingers.

These signals would be transmitted to the Robot and used to command identical Robot limb motion.

Feet Motion

As above, to the extent demanded by the actual system design. For many applications it might be preferable for the Robot to move on wheels rather than on feet. In this case the man might operate foot pedals which would control the motion of the Robot vehicle directly.

Speech

This could easily be incorporated as necessary.

The construction of a system of the type described above would obviously be a major undertaking, involving considerable development. However, even for one of the most difficult subsystems -- remote vision -- the essential basis for a feasible solution exists. The optic nerve data rates seem to be comparable with video state-of-the-art.

APPLICATIONS

As detailed in Table I a wide range of useful space applications is postulated for this Robot system. Additionally such a system would have a number of very useful non-space applications, e.g. exploring the ocean floor, control of dangerous operations, etc.

CONCLUSION

Allowing a man to interact with various extraterrestrial environments is an important part of our space program. This can be done now only by physically transporting the man into the remote environment. An additional method is proposed, in which remote extensions would be provided for the important sensory and motor organs through which man normally interacts with his environment. The extensions would be engineered to match the human system, and would be arranged in semblance of the human form. In this way the man would receive a range of sensory cues -- including feedback

from his own motor actions in the remote environment -- approximating closely to the sensations he would experience were he actually in the remote environment. It is suggested that although development of such a system would be a major undertaking, it appears to be feasible, and might be economic, since it would reduce (in some cases eliminate) the need for life support systems, return capability and the ultra-high reliability that must be built into systems carrying human life. Additionally, once such a system was developed, it would undoubtedly find numerous non-space applications.

ACKNOWLEDGEMENT

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Task	Problem Involved	Present Solution	Proposed Solution	Advantages of Proposed Solution
1. Maintenance and repair of operational satellite systems; eg., communications navigational, meteorological, etc	The cost of these systems is high. To be economic they must therefore have a reasonably long life - eg. 5, 10 or 20 years	Long operational life can be attained by using components with very high reliability, limiting the size and complexity of such systems, replacing defective systems with the launch of a new satellite, etc.	Establishment of an orbiting repair facility with at least two robots (for self-repair) having an inter-orbit maneuvering capability so that faulty satellites can be approached and then repaired by the Robot.	Increase in lifetime of all our operational satellite systems, thus enhancing their economic status. More complex systems can become economically feasible (in spite of a low mean time to failure).
2. In flight repair of manned space-craft.	Under certain circumstances (eg. high radiation flux) it may be very difficult or impossible for an astronaut to go outside the space-craft to make external repairs.	Either use very heavy protective space suits or highly specialised remotely controlled tools.	External repairs to the spacecraft carried out by a general purpose Robot, which will be controlled by an astronaut from within the cabin.	External repairs can be carried out without any danger to the astronauts, and without the need of highly specialised tools.
3. Pilot for orbital military satellites, eg. Dyna-Soar.	Such systems will require either (a) the constant presence of a man in orbit or (b) rapid and reliable deployment of a man into orbit for short unpredictable periods.	Ferrying of astronauts to and from orbit.	Robot permanently stationed in orbit with controller located on earth.	Present methods are so difficult, expensive, impractical etc., as to render virtually infeasible the task of carrying out any sort of space patrol, on an operational basis.
4. Initial Lunar exploration	Very large boosters required to give highly reliable, safe return capability.	Wait for development of very large boosters i.e. probably till 1967-1970.	Soft land robot system with power supplies, communications etc., on to surface of moon. Dispatch human controller to moon orbit (Human controller could be located on earth, but the 2 1/2 sec. communication delay would considerably impair his capability).	Lunar exploration accomplished several years ahead of the first manned mission

TABLE 1 (cont.)

Task	Problem Involved	Present Solution	Proposed Solution	Advantages of Proposed Solution
Detailed exploration and the taking of strategic control of the moon.	As above, and problems of life support during lengthy stays (eg. 50 days) on moon.	Establishment of a lunar base with heat, radiation insulation; oxygen and food supplies, etc.	As in 4.	No life support problem at all on moon. Strategic control taken of moon much earlier than would otherwise be possible. Fabrication of living quarters for eventual manned missions.
Exploration of near planets	Enormous booster required. Entry into strange atmosphere. Landing on strange surface etc. Biological contamination of planet, astronauts, and earth.	No real solution in sight.	Journey by astronauts and robot to planet. Astronauts remain in orbit where they control a robot sent down in a capsule.	Planetary exploration undertaken many years ahead of actual manned exploration. Problems of biological contamination simplified.
Exploration of massive, very cold, or otherwise hostile planets.	It may be physically impossible to maintain life on some planets.	None	As above	Only solution.

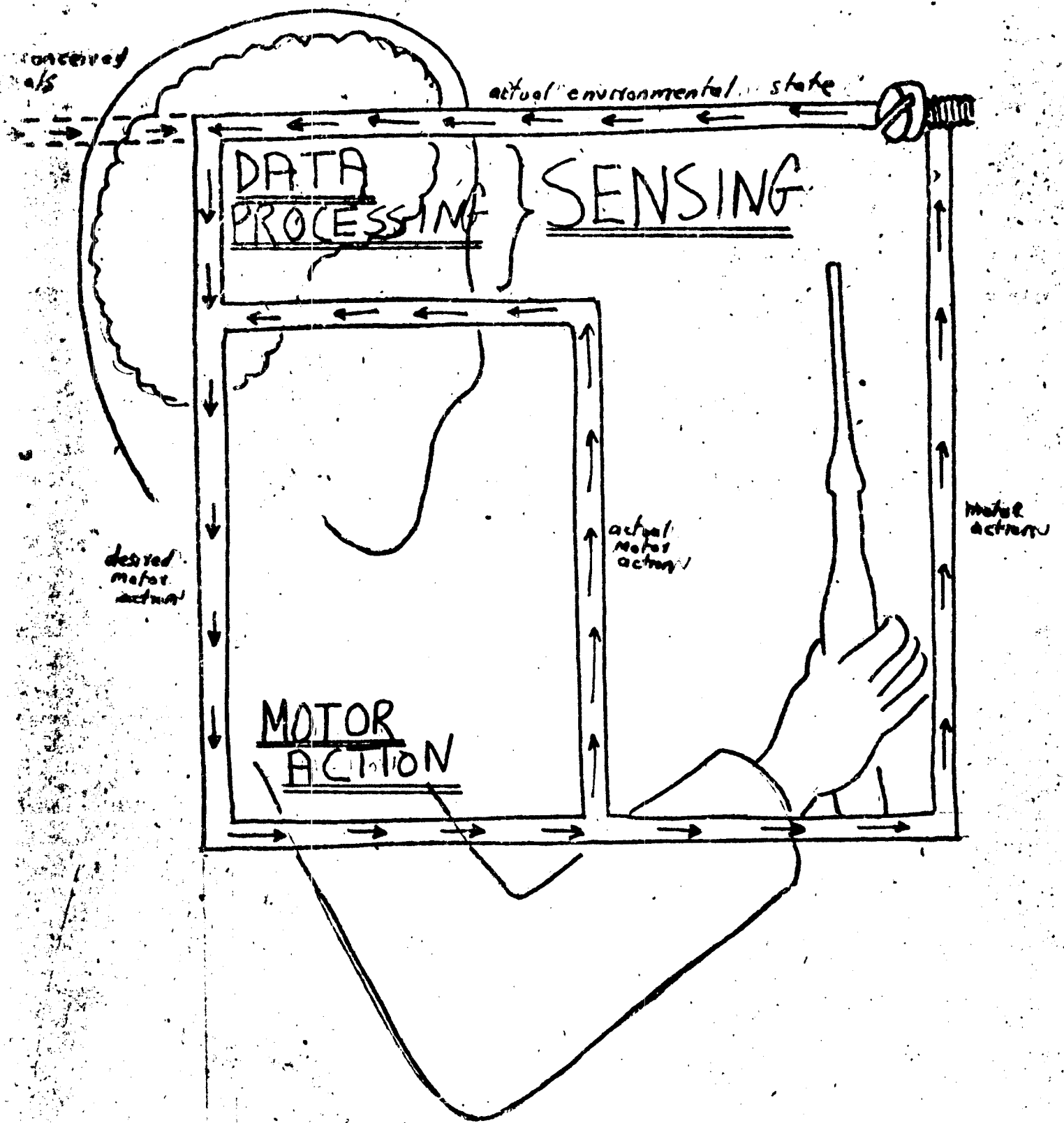


Fig 1 MAN INTERACTING WITH HIS ENVIRONMENT

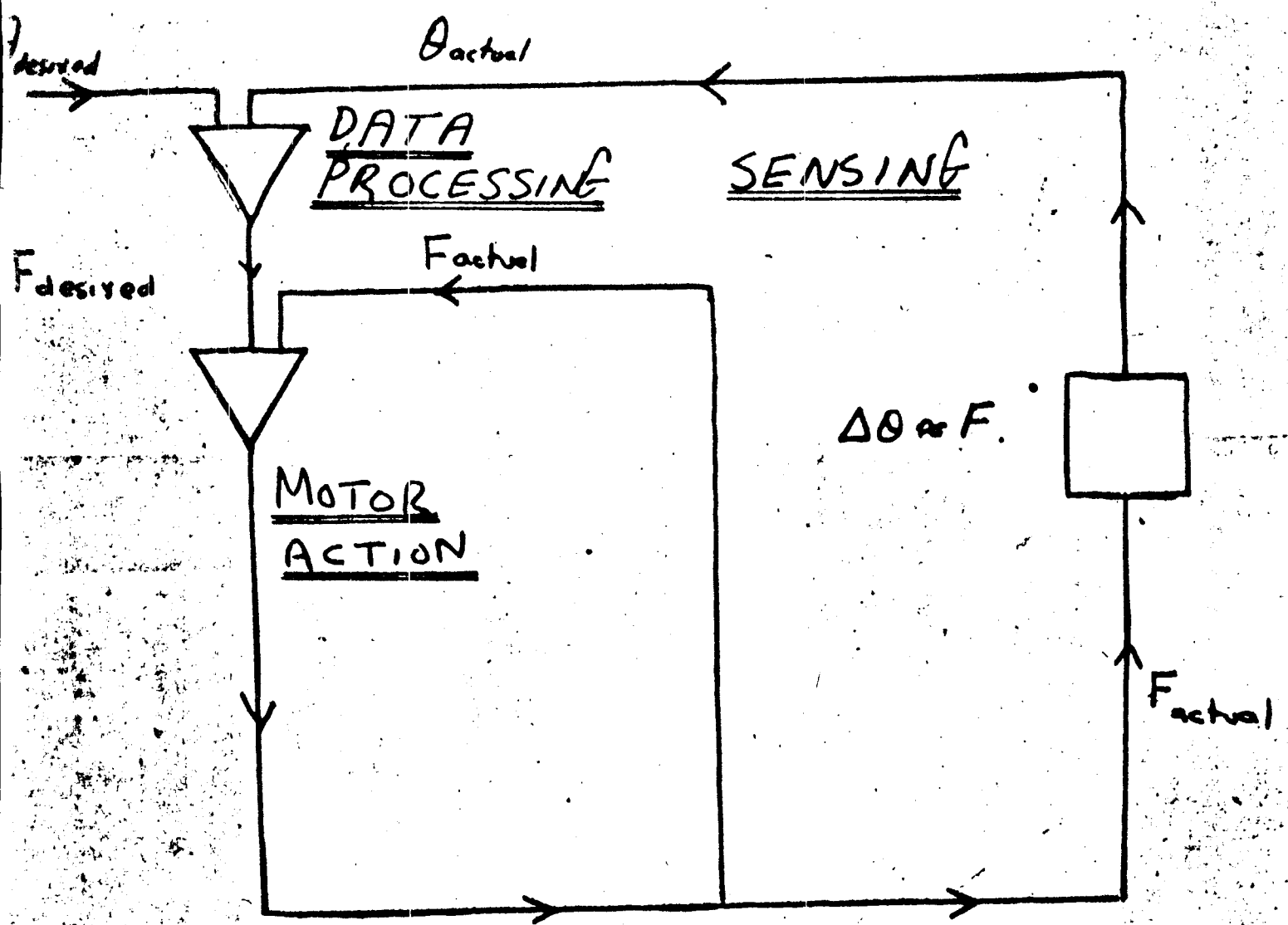


Fig 2 TYPICAL INANIMATE FEED BACK CONTROL SYSTEM